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The abundance of dark galaxies

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ABSTRACT

We show that gas in a large fraction of low mass dark matter halos may form Toomre stable disks, if angular momentum is conserved when the gas contracts. Such halos would be stable to star formation and therefore remain dark. This may potentially explain the discrepancy between the predicted and observed number of dwarf satellites in the Local Group, as well as the deviation between the predicted and the observed faint end slope of the luminosity function. The above mechanism does not require a strong variation of the baryon fraction with the virial mass of the dark halo. We show that model fits to rotation curves are also consistent with this hypothesis: none of the observed galaxies lie in the region of parameter space forbidden by the Toomre stability criterion.

Key words: cosmology: theory — galaxies: formation — galaxies: spiral — galaxies: kinematics and dynamics

1 INTRODUCTION

There is now growing evidence that the observed number of dwarf galaxies surrounding the Milky Way or M31 does not agree with the predictions of high–resolution N-body simulations for the currently favored Cold Dark Matter cosmological model (flat, low matter-density Universe – LCDM) (Klypin et al. 1999; Moore et al. 1999). Given the successes of the current LCDM paradigm in reproducing many of the large-scale observables (e.g., Jaffe et al (2001); Peacock et al (2001); Verde et al. (2001); Lahav et al. (2001)), it seems natural to try to make changes to the existing paradigm without modifying its large-scale properties. There are two routes in this direction: one is to prevent the formation of small dark matter halos, the second is to hide them by suppressing star formation. Some modifications belonging to the first group consist of changing the nature of the dark matter itself to have different physical properties: self–interacting (Spergel & Steinhardt 2000), warm (Colombi, Dodelson & Widrow 1996; Bode, Ostriker & Turok 2001) or other variants (e.g., Goodman (2000); Hu, Barkana & Gruzinov (2000); Cen (2001)). It has also been proposed that the solution to the problem may lie within the nature of the initial conditions and that some modification to the shape of the inflaton potential may suppress small scale structure (Kamionkowski & Liddle 2000), although this solution faces some problems in reproducing the observed amount of structure in the Lyman-α forest. On the other hand, the solution of suppressing star formation via supernova feedback was suggested a long time ago (e.g., White & Rees (1978)). This process expels the gas from the halo and therefore suppresses star formation. The accretion and cooling of gas can also be suppressed in the presence of a strong photo–ionizing background. This route has also been known for a number of years now (Doroshkevich, Zel'Dovich & Novikov 1967) and has been investigated recently in the context of semi–analytic models of galaxy formation (Bullock et al. 2001; Chiu et al. 2001; Somerville 2001; Benson et al. 2001a).

A closely related problem is the fact that the observed faint end of the luminosity function has a shallower slope (Blanton et al. 2001) than predicted from high-resolution LCDM simulations, if one simply assumes a constant mass-to-light ratio (e.g., Jenkins et al. (2001)). Stellar feedback is again often used in semi–analytic models to suppress star formation in halos with shallow potential wells (e.g., Cole et al. (2000)).

All of the above models seek to systematically increase the mass-to-light ratio in small halos, by depleting the cold gas fraction available for star formation. In this paper we show that such drastic expulsion of gas is, perhaps, unnecessary: provided that the gas conserves angular momentum during collapse, a large fraction of low mass halos will be Toomre stable (Toomre 1964; Kennicutt 1989), i.e., $Q = \Sigma_c/\Sigma > 1$ (where Σ is the disk surface mass density and Σ_c is the critical surface density to trigger gravitational instability and thus start formation). If the baryon fraction (f_d) in disks is $f_d \sim 0.5\Omega_b/\Omega_m$, all disks in halos with masses $M < 10^9\, M_\odot$ will be Toomre stable and fail to form stars.

The "missing" dwarf galaxies predicted to be around the Milky Way and M31 may fall in this category. We also show that, if a small fraction of baryons initially present in the dark matter halo settle in a disk, as some observational evidence suggests (Jimenez, Verde & Oh 2002; Guzik & Seljak 2001; van den Bosch, Burkert & Swaters 2001; Burkert 2000; Fukugita, Hogan & Peebles 1998), even more massive halos have some probability of remaining dark, provided they have high spin. This could potentially reconcile the observed luminosity function with the mass function predicted in high–resolution LCDM N-body simulations. We show that the predictions of this model are consistent with our previous analysis of the rotation curves of galaxies (Jimenez, Verde & Oh (2002), hereafter JVO02): none of the galaxies lie in the region of parameter space forbidden by the Toomre instability criterion.

Throughout this paper we assume a LCDM cosmology given by:$(\Omega_m, \Omega_\Lambda, \Omega_b, h, \sigma_8 h^{-1}) = (0.3, 0.7, 0.039, 0.7, 1.0)$.

2 THE MASS DISTRIBUTION OF DARK GALAXIES

We model spiral galaxies as exponential disks embedded in a cold dark matter halo. Following Dalcanton et al. (1997); Jimenez et al. (1997); Mo et al. (1998) we assume a NFW (Navarro, Frenk & White 1997) profile $\rho \propto [(r/r_c)(1 + r/r_c)^2]^{-1}$ where r_c is the break radius and the surface mass density of the disk is given by $\Sigma = \Sigma_0 \exp[-r/Rd]$, where R_d is the scale length of the disk.

For a baryonic disk to be locally gravitationally unstable, despite the stabilizing effects of tidal shears and pressure forces, we require the Toomre parameter $Q < 1$, where:

$$Q = \frac{c_s \kappa}{\pi G \Sigma}, \tag{1}$$

Σ is the disk surface mass density, $\kappa = 1.41(V/r)(1 + \mathrm{d}\ln V/\mathrm{d}\ln r)^{1/2}$ is the epicyclic frequency and c_s is the gas sound speed.

Regions in local disk galaxies where $Q > 1$ are observationally associated with very little star formation, indicating that the Toomre criterion is obeyed remarkably well, if a gas sound speed of $c_s \sim 6\,\mathrm{km\,s^{-1}}$ is assumed (Kennicutt 1989). Ferguson et al. (1996) noted that for one galaxy (NGC 6946) the agreement with the Toomre criterion was not perfect: there was no truncation of star formation for $Q > 1.6$ if the observed vertical velocity dispersion was adopted. However, agreement with the Toomre criterion could be obtained if the velocity dispersion was assumed to be constant with radius. Wong & Blitz (2001) have measured the value of Q in the inner part of rotation curves for a sample of 8 galaxies. For half of the sample the predicted value from Toomre theory for the abundance of gas is in excellent agreement with observations. In the other cases the agreement is not as remarkable, but still there is no evidence for large deviations from the Toomre stability predictions.

Jimenez et al. (1997) developed a disk model to study the dependence of Q on mass, radius and spin parameter of the dark matter halo and found that for a certain range of the above parameters, some disks would be dark. An important ingredient in their study was the assumption of a constant baryon fraction, namely they adopted the nucleosynthesis value from Walker et al. (1991). Using this constant disk fraction for all galaxies, they concluded that for an Einstein–de Sitter Universe the minimum dark matter halo mass for a visible disk galaxy is about 10^9 $M_\odot$. On the other hand, for a low matter density universe (e.g., LCDM), this minimum mass drops substantially, by about two orders of magnitude, and thus the fraction of dark halos also falls drastically. The reason for this is that for a low density Universe with baryon density fixed by nucleosynthesis, the baryons constitute a higher fraction of the halo mass.

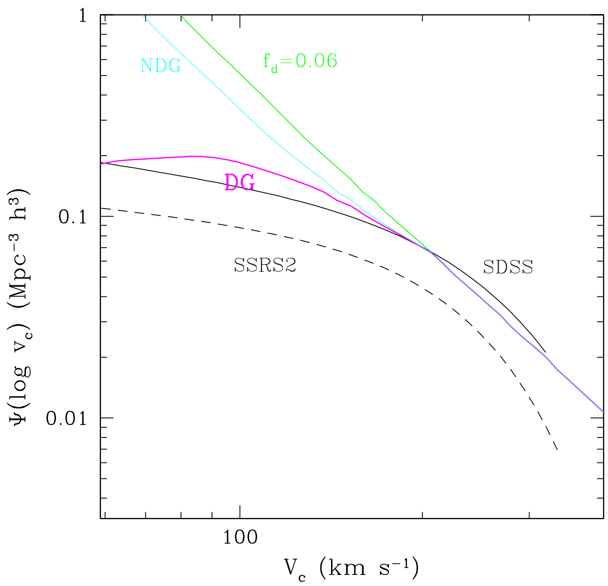

Figure 1. The present day velocity function. Lines labeled by Sloan and SRSS2 are obtained from the SDSS and the SRSS2 surveys respectively. The solid line labeled $f_d = 0.06$ is the theoretical velocity function derived from the Sheth & Tormen (1999) mass function using a constant disk baryon fraction $f_d = 0.06$. The line labeled NDG (no dark galaxies) is obtained assuming our ansatsz for the dependence of f_d on mass (see figure 2). Finally the thick solid line labeled by DG (dark galaxies) is obtained considering that only disks that are Toomre unstable will be able to form stars and thus be visible (see text for more details).

It seems unlikely that all baryons will be able to cool and form stars. Recent studies from galaxy–galaxy lensing from the Sloan Digital Sky Survey (SDSS) show that for L^* galaxies the baryon fraction is about half of the nucleosynthesis value (Guzik & Seljak 2001). On the other hand, theoretical considerations suggest that the baryon fraction for galaxies, either less massive or more massive than L_*, is likely to be much smaller due to feedback and inefficient cooling respectively (e.g. van den Bosch (2001); Benson et al. (2001b)). This implies that a large fraction of disks should be Toomre stable. Below we quantify how this affects the predicted number density of observable galaxies.

2.1 Luminosity function

CDM models typically predict many more galaxies at the faint end of the luminosity function than are actually ob-

served. This can most easily be seen by comparing the galaxy circular velocity function with theoretical predictions. The galaxy velocity function is obtained by combining the observed luminosity function with empirically determined luminosity–velocity relations (Tully-Fisher relation for spirals, and Faber-Jackson for ellipticals). Gonzalez et al. (2000) find that treating the entire galaxy population as spirals does not significantly alter the derived velocity function. In fig. 1, we plot a representative velocity function from their paper, derived from the SSRS2 (Marzke et al. 1998) B band survey and the Yasuda et al. (1997) Tully-Fisher relation. We also construct a new velocity function from the Sloan Digital Sky Survey (SDSS), which has published luminosity functions in 5 bands (Blanton et al. 2001). We choose to use the R band, as the R band Tully-Fisher relation is tighter and has less scatter than the Tully-Fisher relation at shorter wavelengths. Blanton et al. (2001) perform the color transformations from SDSS magnitudes to LCRS (Shectman et al. 1996) R-band magnitudes (see their Table 3); we perform the color transformations and corrections for internal extinction as in Gonzalez et al. (2000) to the $R_{\rm courteau}$ magnitudes used by Courteau (1997). We then use the Courteau (1997) $R_{\rm courteau}$ band Tully-Fisher relation to obtain the velocity function. Note that the Sloan velocity function has a significantly higher normalization than the SSRS2 velocity function. This is due to the use of Petrosian magnitudes for SDSS, which allows detection of galaxies of significantly lower surface brightness. The luminosity density of galaxies in the SDSS is therefore significantly higher than other redshift surveys. The SDSS luminosity function is very similar to the luminosity functions derived by other surveys such as the Las Campanas Redshift Survey (LCRS) and Two Degree Field Galaxy Redshift Survey (2dFGRS) if they re-analyze their data using the shallower isophotal limits for galaxy magnitude employed by these surveys; see Blanton et al. (2001) for discussion.

The theoretical velocity function is given by:

$$\Psi(V_c) = \frac{dN}{d\log V_c} = \frac{dN}{dM}\frac{dM}{d\log(V_c)} f_{\rm bright}, \qquad (2)$$

where V_c is the circular velocity in the flat part of the rotation curve and $f_{\rm bright}$ is the fraction of halos which form stars. For the mass function dN/dM, we use the Sheth & Tormen (1999) mass function, which gives a good fit to the mass function seen in the Hubble Volume simulations (see Jenkins et al. (2001)). For evaluating the derivative $\frac{dM}{d\log(V_c)}$, we use the fitting formula of Mo, Mao & White (1998), which gives the circular velocity V_c as a function of the virial mass of the dark halo (M_{200}), the concentration parameter (c), the spin of the dark halo (λ) and f_d. As in Navarro, Frenk & White (1997), for a given M_{200} we evaluate the concentration parameter from the typical collapse redshift. Below we discuss our choice of f_d, λ further and evaluate $f_{\rm bright}$ using Toomre instability arguments.

Let us start by assuming $f_{\rm bright} = 1$, a constant disk mass fraction $f_d = 0.06$ (i.e., about half the nucleosynthesis value (Fukugita et al. 1998)), and the disk spin parameter to be the mean value found in N-body simulations $\lambda_{\rm mean} = 0.042$ (Bullock et al. 2001). In figure 1 we plot the theoretical velocity function (upper solid line labeled by $f_d = 0.06$). At low velocities, the predicted number density of galaxies is much larger than observed, which is the discrepancy we seek to resolve.

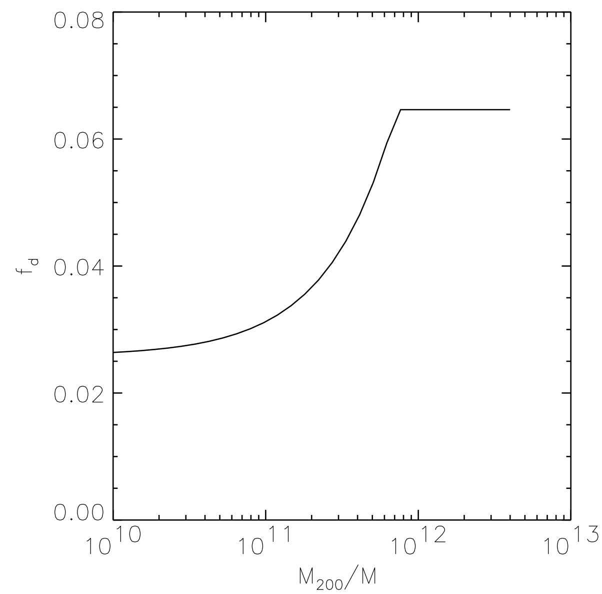

Figure 2. Our ansatz for the mass dependence of the disc baryon fraction f_d. This models a factor of two decline in the value of f_d from high mass to low mass halos, which fits the median value of f_d at high masses (Mo, Mao & White 1998) and low masses (van den Bosch & Swaters 2001).

This cannot be resolved by making f_d a function of M_{200}, unless the $f_d(M_{200})$ dependence is unrealistically drastic. To illustrate this we assume a different functional form for $f_d(M_{200})$, as shown in fig. 2. Our *ansatz* for the $f_d(M_{200})$ relation models a fairly mild factor of two decline in the value of f_d from high mass to low mass halos, which fits the median value of f_d at high masses (Mo, Mao & White 1998) and low masses (van den Bosch & Swaters 2001). If this was the only process at play it would produce only a mild change in the theoretical velocity function, as shown by the thin solid line labeled by NDG (no dark galaxies) in figure 1.

To include the effects of the Toomre instability criterion we proceed as follows. We define a critical spin parameter $\lambda_{\rm crit}$ such that the disc is marginally stable: $Q[f_d(M_{200}), \lambda_{\rm crit}, M_{200}, c(M_{200})] = 1.5$, where Q is evaluated at one disk scale-length, and we assume a gas sound speed $c_s = 6\,{\rm km\,s^{-1}}$ (the gas will in general be photoionized by the meta-galactic ionizing background to $T \sim 10^4$K). The fraction of bright galaxies is given by $f_{\rm bright} = \int_0^{\lambda_{\rm crit}} p(\lambda)d\lambda$, where $p(\lambda)$ is the probability distribution of λ derived from numerical simulations (Bullock et al. 2001). Note that since halos with $\lambda > \lambda_{\rm crit}$ are assumed not to host visible galaxies, the probability distribution of λ in observed galaxies is skewed. We evaluate the circular velocity assuming a median value $\lambda_{\rm median}$, defined by the implicit equation $\int_0^{\lambda_{\rm median}} p(\lambda)d\lambda/f_{\rm bright} = 0.5$. The velocity function we obtain from computing $f_{\rm bright}$ in this manner is shown in figure 1 by the thick solid line labeled by DG (dark galaxies). Thus, once we include the suppression of high-spin galaxies by ex-

plicitly computing $f_{\rm bright}$, the theoretical predictions match the observations well.

The suppression of accretion after reionization (Bullock et al. 2001; Chiu et al. 2001; Somerville 2001; Benson et al. 2001a), is an attractive mechanism for regulating f_d since (unlike for instance, supernova explosions) it affects dark galaxies as well. We model this effect by using the fitting formula (Gnedin 2000; Somerville 2001):

$$f_d^{\rm photo}(M_{200}, z_f) = \frac{\Omega_b}{\Omega_m} \frac{1}{[1 + 0.26 \frac{M_{\rm C}}{M_{200}}]^3} \tag{3}$$

where we approximate M_C as the mass corresponding to a halo with virial velocity $V_c = 50\,{\rm km\,s^{-1}}$ (Somerville 2001) at the redshift of formation $z_{\rm f}$. For a given halo mass M_{200}, extended Press-Schechter theory (Lacey & Cole 1994) gives the probability distribution of collapse redshifts $p(z_f)$; we can then use equation (3) to obtain the probability distribution $p(f_d)$. Note that $f_d = \Omega_b/\Omega_m$ for $z > z_{\rm reion}$, where $z_{\rm reion}$ is the redshift of reionization; we assume $z_{\rm reion} \sim 7$ (the results depend only very weakly on $z_{\rm reion}$).

In the photoionization model, the fraction of dark galaxies can be computed via equation 4, with the probability distribution $p(f_d)$ given above. Significant suppression of the number density of low circular velocity galaxies only takes place off the scales plotted in fig 1. Photoionization only successfully suppresses gas accretion in very small halos; it succeeds in alleviating the dwarf satellite problem, but leaves unaffected halos of $V_c > 75$ Km s^{-1}. By itself it therefore cannot produce the low values of f_d required to reconcile the theoretical and observed velocity function.

We do not attempt to model the $f_d(M_{200})$ relation in more detail (which is the task of hydrodynamic galaxy formation modelling), but merely note that it is consistent with observations and theoretical prejudice that gas expulsion and suppression of accretion are more important for shallow potential wells. Possible mechanisms include suppression of accretion due to entropy injection in the intergalactic medium by supernovae and/or AGN jets, or ram pressure stripping as a smaller halo falls into a larger halo. We note merely that by invoking the Toomre instability criterion, we do not require the very strong variation of f_d with M_{200} required in most semi-analytic models of galaxy formation. In particular, we do not require a very sharp drop in f_d at the faint end.

2.2 The fraction of dark galaxies

In figure 3 we plot the fraction of dark galaxies $f_{\rm dark}$ as a function of halo mass.

The dashed line is $f_{\rm dark} = 1 - f_{\rm bright}$, where $f_{\rm bright}$ has been computed in the previous section. The dotted line shows the resulting $f_{\rm dark}$ if photoionization was the only process at play. As already noted this mechanism only suppresses accretion in halos of low circular velocity and cannot reconcile the observed and theoretical velocity function. Assuming f_d as a deterministic function of M_{200} might be an oversimplification: in reality f_d is likely to be highly stochastic (e.g., van den Bosch (2001); Benson et al. (2001b)). Also, analysis of rotation curves (JVO02) confirms that there is a significant scatter in the relation (see §3). We thus compute also the expected fraction of dark galaxies by neglecting any possible mass dependence and using the distribution of f_d ($p(f_d)$) empirically obtained by fitting the rotation curves for the NFW profile (see JVO02 and §3):

$$f_{\rm dark} = \int_{\lambda_{crit}}^{\infty} d\lambda \int_0^{f_{d\,\rm crit}} df_d \, p(f_d) \, p(\lambda) \tag{4}$$

where $\lambda_{\rm crit}$ and $f_{d\,\rm crit}$ are defined by $Q(M_{200}, f_{d\,\rm crit}, \lambda_{\rm crit}, c) = 1$. The result is shown in figure 3 as a solid line. The two approaches (the one described in §2.1 or using the empirically obtained f_d distribution) yield very similar values for $f_{\rm dark}$, indication of the fact that the main mechanism to create dark galaxies is the Toomre criterion.

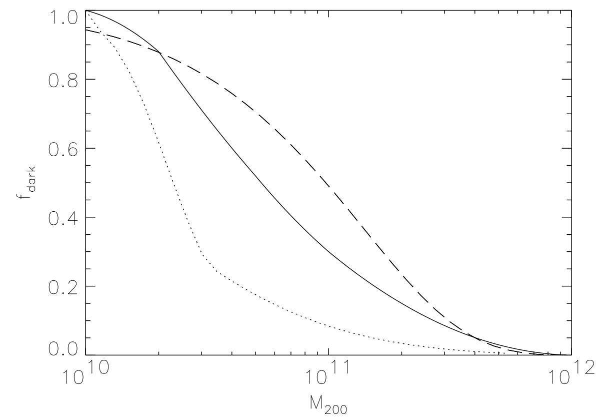

Figure 3. Fraction of dark galaxies $f_{\rm dark}$ as a function of halo mass. The dashed line is $f_{\rm dark} = 1 - f_{\rm bright}$, where $f_{\rm bright}$ has been computed in §2, by considering the Toomre instability criterion and a mild mass dependence of the disk baryon fraction f_d shown in fig 2. The dotted line shows the resulting $f_{\rm dark}$ if suppression of accretion due to reionization determines f_d. The solid line is the dark fraction derived using the distribution of f_d empirically obtained by fitting the rotation curves.

2.3 Dwarf satellites

From fig. 3 it is clear that star formation within dark matter halos with masses below 10^{10} M$_\odot$ will be almost completely suppressed (not visible because they will be Toomre stable). Thus this provides a mechanism to hide these low mass halos. To make a more quantitative estimate of the viability of this effect, in figure 4 we compare the observed cumulative mass function of dwarf satellite with predictions from N-body simulations. The solid line is from Moore et al. (1999), where the velocity has been converted in mass. The gray area is an estimate of the error from fig. 2 of Moore et al. (1999). The solid and dashed lines are the predicted cumulative number of satellites once the probability that some galaxies will remain dark has be taken into account. In particular we have used the predictions of the solid and dashed lines of figure 3 respectively. This prediction agrees nicely with observations (triangles). We have not shown results for masses below 10^9 M$_\odot$ because the uncertainties in the procedure to obtain the corrected line become too important; only a very small fraction ($< 1\%$) of dark matter halos will be visible thus making this fraction very dependent on the exact value of the predicted number of dark galaxies.

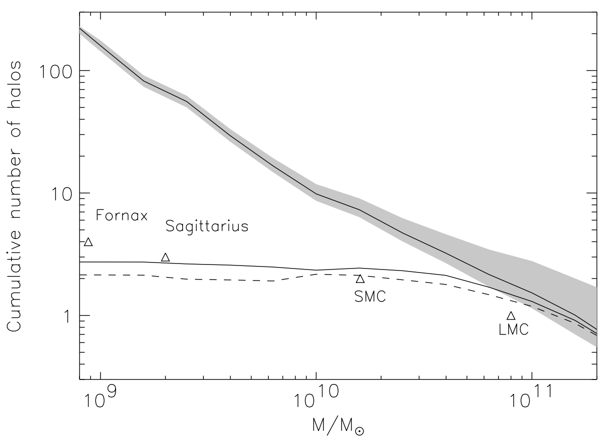

Figure 4. Cumulative mass function of dwarf satellites of the Milky Way. Small triangles are the observations, the solid line with the gray area is the predictions from N-body simulations with an estimate of the uncertainty. Finally the solid and dashed dashed lines show the predictions once the the probability that some halos will remain dark (due to their spin parameter being above the critical value) has be taken into account. Solid and dashed lines have been computed using the $f_{\rm dark}$ fraction of fig. 4.

3 ROTATION CURVES

In this section we present some indication of the existence of dark galaxies from analysis of a large sample of rotation curves.

We use the same set of rotation curves as in JVO02 where we determined the best fit disk parameters within the context of both a disk within a NFW profile halo and within a pseudo-isothermal profile halo (see JVO02 for details).

The two sets of observed rotation curves are:

- Courteau catalog (Courteau 1997) which consists of optical (H_α) long–slit rotation curves for 300 Sb–Sc UGC galaxies.
- 64 spiral galaxies (Sa–Sd) observed in H_α by Palunas & Williams (2000)

In total we use 364 optical rotation curves (to avoid any problems with the smearing of the beam in radio observations (van den Bosch & Swaters 2001)) corrected for inclination and with error bars. For these galaxies the scale length of the exponential disk (R_d) is also measured. The two models have three free parameters: M_{200}, r_c, and f_d. In principle there is another disk parameter: the modified spin parameter λ'. If λ is the spin parameter of the dark halo, then $\lambda' = j_d/f_d\lambda$ where $j_d \equiv J_d/J$ and J_d, J are the total angular momentum of the disk and halo respectively. λ' can be readily obtained using the measured value of R_d and the best fit parameters (see JVO02). If angular momentum is conserved, then $\lambda = \lambda'$, i.e. $j_d/f_d = 1$.

In JVO02 we used the sample of 364 galaxies for which R_d is measured, we found the best fitting parameters (M_{200}, f_d, and c) for the above two models and recovered λ'. Within both models for the majority of the galaxies, a meaningful set of fitting parameters was recovered. For the remaining galaxies we obtained values for f_d that where either implausibly low ($f_d \simeq 0.001$) or may be too high ($f_d \gtrsim 0.2$).

3.1 Fit to the disk models

As described in detail in JVO02, for each galaxy rotation curve and for both models, the best fitting parameters were obtained using a standard χ^2 minimization and exploring the whole likelihood surface. The sample of galaxies studied is very non-uniform: some curves have much smaller error-bars than others, some curves do not extend to large enough radii to show the flattening of the rotation curve, while others show strong evidence of spiral arms and bars in the rotation pattern, moreover we have not attempted to model any bulge nor bar component. Thus it is is important to keep in mind that galaxies might be more complicated than our model for galaxy rotation curves. However, for most of these galaxies, the high-quality of the rotation curves measurements allow degeneracies among the disk parameters to be lifted (JVO02). Here, we are not interested in a detailed modeling of individual galaxy dynamics but rather the general statistical trends of the recovered disk parameters from the whole sample.

Fig. 5 shows the distribution of the best fitting disk parameters in the f_d-λ' plane and M_{200}-f_d plane, for the NFW profile (top) and pseudoisothermal profile (bottom); diamonds correspond to galaxies from the Courteau (1997) sample and triangles are from Palunas & Williams (2000). In JVO02 we showed that low surface brightness galaxies (LSBs) follow the same trend as the rest of the sample, so any observational bias against LSBs does not seem to affect this result: the only difference is that LSBs have systematically higher values of λ' for a fixed value of f_d. In both models there is a correlation between λ' and f_d, albeit with a scatter, and a weak anti-correlation between M_{200} and f_d.

For $f_d < 0.02$, λ' values are between 0.01 and 0.03, while for $f_d > 0.02$, λ' takes all values between 0.02 and 0.4.

The origin of this correlation is controversial: van den Bosch (2001) argues that when feedback by star formation is included in models of galaxy formation, such a correlation between λ' and f_d arises naturally for low mass galaxies, where feedback is most efficient; Burkert (2000) showed that it can be an effect of disk growth happening inside-out; or disks might preferentially lose baryons with high angular momentum. On the other hand, Burkert, van den Bosch & Swaters (2002) argue that the correlation may be entirely due to intrinsic degeneracies due to the fact that from rotation curves analysis the total dark halo mass is not well constrained. In JVO02 (figure 14) we find that this is the case for rotation curves that are not measured at large enough radii, but, for most of the galaxies in the sample (70%), the high-quality rotation curves allow model degeneracies to be lifted. This indicates that the random error in recovered parameters is small. On the other hand, the systematic errors (especially due to the uncertainty in the dark matter profile) may be larger, possibly causing the correlations.

We argue here that the most significant feature of the left panels of fig. 1 *is not the correlation itself*, but the fact that spirals avoid the upper left portion of the λ'–f_d plane and that this is in agreement with the Toomre instability criterion. In passing we also note that disk instability might make galaxies with disk parameters in the bottom left corner of the plot to drop out of the sample: for these parameter values discs might be too concentrated and form a spheroidal instead of a disc or galaxies might become bulge dominated.

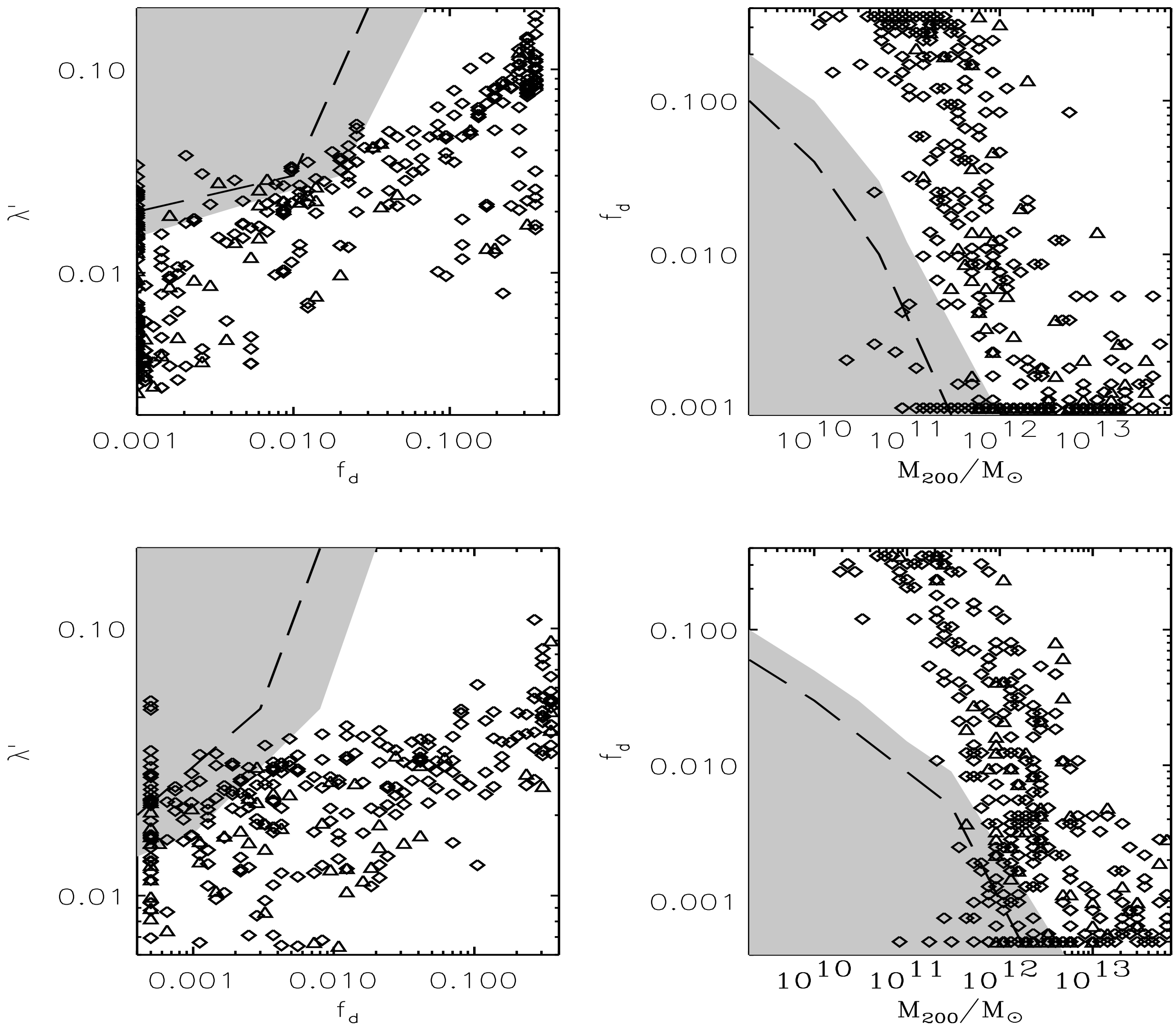

Figure 5. Distribution of the best fitting disk parameters in the f_d-λ' plane and in the $f_d - M_{200}$ plane for the NFW (top) and pseudoisothermal profile (bottom). We argue that the Toomre instability criterion correctly predicts the zone of avoidance (gray shaded areas) for combinations of disk parameters that involve low M_{200} and low f_d. Note that there seems to be another small void region in the bottom right corner of the f_d-λ' plot. This might arise because for these parameter values discs might be too concentrated and form a spheroidal instead of a disc.

The right panels show an interesting, although weak, correlation between M_{200} and f_d: low mass spirals ($M_{200} < 10^{11} M_{\odot}$) tend to have $f_d > 0.1$ since no galaxies are found in the lower left portion of the plot. There can be several different effects that module the dependence of f_d on the halo mass. Linear theory evolution from inflation predicts a weak anti correlation between spin parameter and peak height (Heavens & Peacock 1988), and hence mass of the halo. The expected anti correlation is, however, very weak. On the other hand, cooling is less efficient in massive halos ($M_{200} \gtrsim 10^{12} M_{\odot}$), thus f_d is expected to *decrease* strongly with increasing M_{200} (e.g., van den Bosch (2001)) at the high mass end. However, in small mass halos, reheating of cooled gas through feedback and photoionization processes are much more efficient than in massive systems, thus implying that f_d should *increase* with M_{200} (e.g., Benson et al. (2001b)) at the low mass end. The correlation we find from rotation curves analysis is in rough agreement with the high-mass end trend (see fig. 5 of van den Bosch (2001)). For his no feedback model, the baryon fraction decreases for increasing masses. For the feedback model this is only true for M_{200} bigger than $\sim 5 \times 10^{11}$ M$_{\odot}$. For lower masses this trend reverses and we do not find evidence for it from our analysis of rotation curves. This may be due to the fact that for these low masses, only those galaxies with highest f_d are visible.

Here we show that Toomre instability criterion predictions are in agreement with the zone of avoidance for combinations of disk parameters that involve low M_{200} and low f_d or low λ.

3.2 Stability of discs

The void areas found in fig. 5 can be explained by resorting to the Toomre instability criterion: for $Q > 1$ the gas disc is stable and thus star formation is strongly suppressed. Expressions for Q and Σ for the NFW profile have been presented in Jimenez et al. (1997), here we derive the corresponding expressions for the pseudoisothermal profile.

Recall that in the pseudoisothermal profile the density ρ as a function of the radius r is $\rho(r) = \rho_0[1 + (r/rc)^2]^{-1}$, where ρ_0 denotes the central finite density. The disk surface density as a function of the radius is $\Sigma(r) = \Sigma_0 \exp(-r/R_d)$, where $\Sigma_0 = f_d M_{200}/(2\pi R_d^2)$. Appendix I of JVO02 gives a relation between ρ_0 and the concentration parameter c and a fitting formula for R_d as a function of the disk parameters: M_{200}, ρ_0, r_c and λ'.

The shaded areas in figure 5 represent the void regions predicted by the Toomre criterion assuming $c_s = 6$ km s^{-1} for all values of masses and radii. The dashed line shows how the avoidance region would change if $c_s = 2$ km s^{-1}. Such a low value is based on the findings of Corbelli & Salpeter (1995), who argue that when the quasar UV ionizing background is the only source of ionization of the HI gas, as should be the case for dark galaxies with no supernova, then the sound speed of the gas cannot be higher than 2 km s^{-1}. Measured values of the sound speed in the Milky Way and in nearby galaxies (see e.g., Kennicutt (1989)) range between 3 and 10 km s^{-1}. Note that using a low value for c_s is a conservative assumption, since for small values of the velocity dispersion the formation of dark galaxy is more difficult.

More specifically, for a grid in M_{200}, λ', f_d, we compute the surface density of the exponential disc Σ and whether $Q > 1$. The shaded area in the left panels of fig. 5 are obtained assuming a fixed mass of 5×10^{11} M$_\odot$, approximately in the middle of the mass range considered. The shaded area in the right panels is obtained as follows: we assume a log-normal distribution of spin parameters with mean 0.042 and dispersion 0.5 (Bullock et al. 2001), thus 68% of galaxies are expected to have $\lambda' > \lambda'_{68} \equiv 0.033$. We then assume that a combination of f_d and M_{200} parameters correspond to a dark galaxy when for all $\lambda' > \lambda'_{68}$ the disc is Toomre stable. The Toomre criterion seems to work better for the NFW profile than for the pseudoisothermal.

However, for the pseudoisothermal profile model there is no theoretical prediction for the expected λ' distribution and the dependence of the concentration parameter $c \equiv R_{200}/r_c$ on the halo mass. To produce the gray areas in fig. 5 we assume the same log-normal distribution for λ as predicted from CDM simulations. This assumption should be valid since JVO02 find that the empirically recovered λ' distribution is well approximated by the CDM prediction. For setting the concentration parameter we consider that, when a galaxy rotation curve is fitted by the pseudoisothermal profile, r_c obtained is about 1/10 of that obtained when the curve is fitted by the NFW profile (fig. 5 of JVO02). Thus, for a given mass, we compute the concentration parameter as expected in the NFW profile, and convert it to the pseudoisothermal one. The scatter around this relation is, however, quite large, thus introducing some uncertainty in the grey areas so obtained.

The Toomre criterion is a local instability criterion; global instabilities can in principle trigger star formation. For example discs in which the self gravity is dominant are likely to be unstable to the formation of a bar. Here we use the results of Efstathiou, Lake & Negroponte (1982) and Mo, Mao & White (1998) to conclude that the onset of these instabilities does not affect the grey areas.

We conclude that the Toomre criteria at least in the context of a NFW profile seems to predict correctly the region of the parameter space that galaxies tend to avoid (i.e., these galaxies should be dark).

4 DISCUSSION AND CONCLUSIONS

In this paper we propose that gas in a large fraction of low mass dark matter halos may form Toomre stable disks. Such halos would be stable to star formation and therefore remain dark. This may potentially explain the discrepancy between the predicted and observed number of dwarf satellites in the Local Group, as well as the deviation between the predicted and the observed faint end slope of the luminosity function. We show that model fits to rotation curves are consistent with this hypothesis: none of the observed galaxies lie in the region of parameter space forbidden by the Toomre stability criterion. Such Toomre stable disks may be the origin of damped Lyα systems seen at high redshift (Kauffmann 1996; Jimenez et al. 1998; Mo et al. 1998).

Most semi-analytic models of galaxy formation achieve a reconciliation between the observed and predicted abundance of low luminosity galaxies by drastically decreasing f_d for faint galaxies. At present, there is no evidence from rotation curve modelling that low circular velocity disks are dark matter dominated (which would be the case if f_d were very small). Our model only requires a very gentle decline in f_d toward low masses. It magnifies the effect of previously proposed mechanisms (e.g. supernovae feedback, suppression of accretion), since $Q \propto f_d^{-1}$ and low f_d disks are more likely to be Toomre stable; *such mechanisms can therefore be 'tuned down' to lower levels.* This may be relevant to the problem of trying to simultaneously fit the luminosity function and the Tully-Fisher relation. In our model, the mass-to-light ratio is much more stable as a function of halo mass (except in dark halos, where it is infinite). Indeed, by construction we fit both the Tully-Fisher relation and the luminosity function, since both were used to obtain the velocity function.

Jimenez et al. (1997) proposed that disks in high spin halos may not be low surface brightness galaxies but instead be completely dark. This was at variance with the proposal that a large fraction of the 'missing galaxies' lie in low surface brightness galaxies which formed preferentially in high spin halos (Dalcanton, Spergel & Summers 1997). Here, we have extended the Jimenez et al. (1997) model to a LCDM scenario and show that it is supported from an analysis of rotation curves. If it is true that disks in such high spin halos may not be low surface brightness but instead be completely dark, then there should be a cutoff in the surface brightness distribution of galaxies; as surveys probe increasingly low surface brightness galaxies the luminosity density will not continue to increase but instead will plateau.

It is important to consider independent indications for the existence of this dark galaxy population and devise possible observational tests. For example, Augusto & Wilkinson

(2001) and Trentham, Möller & Ramirez-Ruiz (2001) have investigated the detectability of dark objects.

These dark galaxies have very low surface densities of HI (below 10^{20} cm^{-2} at one scale length of the disk), still high enough to be detected by current surveys (Zwaan 2001) if the HI was in its neutral phase. Current observations that are sensitive enough to detect such amount of neutral HI have been carried out recently by Charlton et al. (2000); Zwaan & Briggs (2000); Zwaan (2001). In particular, Zwaan (2001) found no significant detection of HI, down to a detection limit of 7×10^{6} M$_{\odot}$, not associated with visible galaxies. Therefore, it seems not likely that large masses of neutral HI are harbored in dark galaxies. This should not come as a surprise, since, given the low surface densities, the hydrogen might be ionized by the extragalactic background. At densities below 10^{19} cm^{-2}, HI is not able to self-shield from the external radiation field and most of it will be in its ionized phase. Another possibility is that, due to pressure ram stripping from the hot gas of the hosting large galaxy, most of the HI gas could be removed from the dark galaxy (Quilis, Moore & Bower 2000).

A more promising route to detect the presence of dark galaxies is through their gravitational lensing properties. Recently Metcalf & Zhao (2001); Dalal & Kochanek (2001); Keeton (2001); Bradac et al. (2001) have discussed the need of substructure to explain the relative fluxes of multiple lensed systems. They show that the flux ratios observed in each lens can only be explained by the presence of substructure within a large smooth halo. This population would be similar to our dark galaxies.

Dark galaxies with dark halo masses above 10^{10} M$_{\odot}$ should be directly visible via strong gravitational lensing. They will produce splitting angles $\lesssim$ 0.1 arc second, which is just below detection with current technology, but will be easily observable with future radio interferometers (e.g., VLBI)

Using the metallicity distributions of globular clusters, Cote, West & Marzke (2001) conclude that the mass spectrum of proto-galactic fragments for the galaxies in their sample has a power law with index ~ -2, indistinguishable from that predicted from N-body simulations. They argue that the missing satellite population must therefore belong to a class of dark galaxies, similar to the ones we consider here.

The biggest caveat in our model is the assumption of conservation of angular momentum. In principle angular momentum loss is possible due to torquing by substructure in the dark matter halo; indeed, it is invariably seen in SPH simulations of disk galaxy formation. This results in more compact disks which are much more susceptible to gravitational instability. However, both fits to the scale lengths of disks (Mo, Mao & White 1998) and modeling of the rotation curves (Jimenez, Verde & Oh 2002; van den Bosch, Burkert & Swaters 2001) recovers spin parameters consistent with the log-normal distribution seen in dissipationless N-body simulations, indicating little or no loss of angular momentum. In addition, we have ignored the effect of mergers; as halos merge their disks are likely to be disrupted and transformed into spheroidal systems, which again are more likely to become self-gravitating. The merger history of halos is well handled in semi-analytic models of galaxy formation which employ Press-Schechter based Monte-Carlo merger trees. It would be very interesting to incorporate the additional physics of Toomre stability into pre-existing semi-analytic (or hydrodynamic) galaxy formation models to compare its importance against various other proposed schemes for suppressing star formation in low mass halos.

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